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THE HOST GALAXY OF GRB 060505: HOST ISM PROPERTIES

Emily M. Levesque and Lisa. J. Kewley
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Dr., Honolulu, HI 96822
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ABSTRACT

We investigate the ISM environment of GRB 060505. Using optical emission-line diagnostic ratios, we compare the ISM properties of the GRB 060505 host region with the hosts of unambiguous long- and short- duration GRBs. We show that the metallicity, ionization state, and star formation rate of the GRB 060505 environment are more consistent with short-duration GRBs than with long-duration GRBs. We compare the metallicity and star formation rates of the GRB 060505 region with four other star-forming regions within the GRB 060505 host galaxy. We find no significant change in metallicity or star formation rate between the GRB 060505 region and the other four host regions. Our results are consistent with a compact-object-merger progenitor for GRB 060505.

Subject headings: gamma-ray bursts

1. INTRODUCTION

The nature of the GRB 060505 progenitor is currently a topic of hot debate. GRBs are the signatures of extraordinarily high-energy events. Burst length distinguishes between "short" (< 2 s) bursts arising from compact-object mergers (Gehrels et al. 2005) and "long" (> 2 s) bursts with massive core-collapse progenitors (Woosley 1993) that are commonly accompanied by luminous and broad-lined Type Ic supernovae (Watson et al. 2007). GRB 060505 has a burst length of ~ 4 s, but notably lacks evidence of an accompanying supernova. Investigations into the host properties of GRB 060505 strongly disagree on the nature of the progenitor. It is unclear whether GRB 060505 originates from a compact-object merger, a massive core-collapse supernova, or a new class of long-duration GRBs with no associated supernovae. The nature of GRB 060505 may have important implications for our classification and understanding of GRB progenitors.

GRB 060505 was observed on UTC 2006 May 5 by the Swift Burst Alert Telescope (BAT) (Hullinger et al. 2006; Palmer et al. 2006), associated with the $z = 0.0889$ galaxy 2dFGRS S173Z112 (Colless et al. 2003; Ofek et al. 2006; Thöne et al. 2006a; Fynbo et al. 2006). It was initially categorized as a long-duration GRB based on its ~ 4 s burst length (Kouveliotou et al. 1993). Thöne & Fynbo (2007) find a lower metallicity and higher rate of star formation at the GRB 060505 burst site when compared with other regions of the host galaxy. Recent investigations suggest that long-duration GRBs are associated with low-metallicity star-forming environments (Stanek et al. 2006, Sollerman et al. 2005, Fruchter et al. 2006, Kewley et al. 2007, Brown et al. 2007), supporting a core-collapse progenitor scenario for GRB 060505.

On the other hand, GRB 060505 may be the product of a compact-object merger with a longer-than-average burst duration. Short- and long-duration GRBs are separated by a burst-duration cut-off of 2 s, but there may be some overlap between these two classes of progenitor events; short-burst progenitors have a 12% chance of yielding a burst longer than 4 s (Horváth 2002).

Electronic address: emsque@ifa.hawaii.edu, kewley@ifa.hawaii.edu

Additional support for a compact-object merger progenitor for GRB 060505 includes the progenitor's evolutionary timescale, the spiral nature of the host galaxy, and the brightness of the burst region. Ofek et al. (2007) calculate an upper limit of 10 Myr for the progenitor birth-to-explosion timescale of the GRB 060505 event. While this age limit does not rule out the possibility of a core-collapse progenitor, such a timescale is also consistent with the merging of two neutron stars or a neutron star-black hole merger, both of which are compact object merger scenarios associated with short bursts (Belczynski et al. 2006). The host galaxy of GRB 060505 is categorized as an Sbc spiral, which is unusual for a long-duration GRB host galaxy (Thöne & Fynbo 2007). Fruchter et al. (2006) found that long-duration GRBs favor the brightest regions of their host galaxies that are associated with concentrated populations of young massive stars (van den Heuvel & Yoon 2007). The GRB 060505 progenitor region is relatively faint compared to its host galaxy, supporting a compact-object merger progenitor (Ofek et al. 2007).

Alternatively, GRB 060505 may belong to a new class of long-duration GRBs with no associated supernovae. The distribution of known GRB burst durations suggest the existence of a third category of GRBs (Mukherjee et al. 1998, Horváth 2002). GRB 060505 is often compared with GRB 060614, a ~ 102 s burst (Barthelmy et al. 2006) classified as a long GRB with no apparent supernova counterpart - both have been proposed as representative examples of a new class of GRBs (Fynbo et al. 2006, Jakobsson & Fynbo 2007, King et al. 2007).

Schaefer & Xiao (2006) suggest that GRB 060505 is a background event that has been associated with 2dF-GRS S173Z112 by coincidence. However, Watson et al. (2007) estimate that the superposition of the burst directly over a star-forming region of low metallicity would be unreasonably serendipitous.

There are several reasons to believe that the progenitors of long-duration bursts would favor low-metallicity environments. Mass loss in late-type massive stars, driven by radiation pressure on spectral lines, is heavily dependent on metallicity (Vink & de Koter 2005), with mass loss and metallicity correlated by the rough

relation $\dot{M}_w \propto Z^{0.78}$ (Mokiem et al. 2006). Surface velocities are also expected to be higher for such stars at low metallicity, a consequence of the lower mass loss rate and an important property of collapsars (Kudritzki & Puls 2000, Meynet & Maeder 2005). The host environments of long-duration GRBs should also have high ionization parameters, since the typical age of the young stellar populations in long-duration bursts is consistent with late-type massive stars that dominate the radiation field, such as Wolf-Rayet stars (Kewley et al. 2007). There is no evidence that a compact-object-merger progenitor would favor such an environment: compact-object mergers are found in many galaxy types (such as ellipticals and spirals, including early-type spirals,) that typically have older stellar populations (and, therefore, less ionizing radiation) and considerably smaller star formation rates (Nakar 2007). These hosts typically have higher metallicities than the blue compact dwarf galaxy hosts of core-collapse-progenitor long GRBs (Bloom & Prochaska 2006). These characteristics suggest that the ISM properties of these two host environments should be distinct.

In this paper, we compare the ISM properties of GRB 060505's host galaxy to long and short GRB hosts, as well as a large sample of blue compact galaxies. We show that GRB 060505 has a unique set of ISM properties that leads to insight into the puzzling nature of its progenitor. Throughout this paper we assume a cosmology of $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. EMISSION LINE FLUXES

We use emission line fluxes from Thöne et al. (2007) for five different regions of the host galaxy: (a) the site of the gamma-ray burst, (b) the upper, (c) middle, and (d) lower regions of the galaxy's bulge, and (e) a region of the galaxy's lower spiral arm.

Our comparison sample is composed of sixty-seven blue compact galaxies (BCGs) from the spectroscopic study of Kong & Cheng (2002), and seven long- and two short- duration GRB host galaxies from the GHostS public archive (Savaglio et al. 2006) . The reference sources for these fluxes are given in Table 1.

All LGRB fluxes were corrected for local extinction effects based on the Hα/Hβ emission line ratio where possible. We use the Cardelli, Clayton & Mathis (1989) reddening curve, assuming an $R_V = Av/E(B - V) = 3.1$ and an intrinsic Hα/Hβ ratio of 2.85 (the Balmer decrement for case B recombination at T= 10^4K and $n_e \sim 10^2 - 10^4$cm^{-3}; Osterbrock 1989). The E($B - V$) values applied are given in Table 1.

Hα line fluxes were unavailable for the short GRB hosts. In these cases we estimate the extinction using the E($B - V$)-M_B relation in Jansen et al. (2001). We use M_B for GRB 051221 and GRB 050416 from Soderberg et al. (2006, 2007), respectively. The resulting extinction values are ~ 0.3, consistent with the mean extinction for the Nearby Field Galaxy Survey (Kewley, Jansen & Geller 2005), and with the mean extinction of star-forming galaxies in the Sloan Digital Sky Survey (Kewley et al. 2007).

3. LINE RATIO DIAGNOSTICS

In figures 1 and 2 we show the common line diagnostic diagrams proposed by Veilleux & Osterbrock (1987),

Baldwin et al. (1981), and Dopita et al. (2000). For comparison, we show representative Mappings photoionization grids from Kewley et al. (2001). These grids model a continuous star formation history, using the Starburst99 v3.0 stellar population synthesis models and the Mappings III photoionization models with an electron density of 350 cm^{-3} and an age of 4 Myr. The grids shown here have ionization parameters ranging from $q = 5 \times 10^6$ to 3×10^8 cm s^{-1} and metallicities ranging from $Z = 0.09Z_\odot$ to $Z = 3.5Z_\odot$, where solar metallicity is log(O/H) + 12 = 8.7 (Allende Prieto, Lambert, & Asplund 2001). We discuss each diagram separately below.

3.1. [NII]/Hα vs. [OIII]/Hβ

The [NII]/Hα ratio is correlated strongly with metallicity and ionization parameter (Veilleux & Osterbrock 1987, Kewley & Dopita 2002). The [OIII]/Hβ ratio is sensitive to the ionization parameter of a galaxy and the hardness of the ionizing radiation field (Baldwin et al. 1981). From Figure 1 we can see that the long GRB host galaxies are concentrated in the upper region of the diagnostic diagram ($0.688 < \log([OIII]/H\beta)_{LGRBs} < 0.932$), with the short GRB hosts in the lower region of the diagram ($0.161 < \log([OIII]/H\beta)_{SGRBs} < 0.452$). The BCG sample spans a much broader range of [OIII]/Hβ ratios ($-0.245 < \log([OIII]/H\beta)_{BCGs} < 0.990$).

Examining the placement of GRB 060505's burst site on this diagram, we see that the [OIII]/Hβ ratio of the GRB site ($\log([OIII]/H\beta) = 0.520$) places it well *below* the region delineated by the long GRB hosts, lying closer to the region occupied by the short GRB hosts. Its [NII]/Hα ratio cannot distinguish it from long or short GRB hosts. The other regions of GRB 060505's host galaxy all have higher [NII]/Hα ratios and lower [OIII]/Hβ ratios than the long GRB hosts, occupying the same region as the short GRB hosts in Figure 1.

3.2. [NII]/[OII] vs. [OIII]/[OII]

As described by Baldwin et al. (1981), the [NII] and [OII] fluxes are directly proportional to a galaxy's high-ionization volume, while the [OIII] flux is directly proportional to the low-ionization volume. This makes the [NII]/[OII] vs. [OIII]/[OII] diagnostic (Figure 2) a powerful means of measuring a galaxy's ionization parameter, with [NII]/[OII] primarily sensitive to metallicity and [OIII]/[OII] primarily sensitive to ionization parameter.

In Figure 2 there is a large separation between the [OIII]/[OII] ratios (or ionization parameters) of the host galaxies; long GRBs ($0.380 < \log([OIII]/[OII])_{LGRBs} < 1.053$) and short GRBs ($-0.409 < \log([OIII]/[OII])_{SGRBs} < -0.108$). The BCG sample spans a much larger range ($-0.994 < \log([OIII]/[OII])_{BCGs} < 0.952$).

The [OIII]/[OII] ratio of the GRB 060505 burst site ($\log([OIII]/[OII]) = -0.108$) lies well below (0.5 dex) the region of the long GRBs, instead resting at the upper limit of the short GRB region. The [NII]/[OII] ratio of the burst site agrees well with the long GRB hosts and BCGs. The other regions of GRB 060505's host galaxy show similarly intermediate [NII]/[OII] ratios and [OIII]/[OII] that are consistent with the short GRB host region.

The metallicity-sensitive [NII]/[OII] ratio suggests that the GRB 060505 burst site has a marginally lower metallicity than the other regions of its host galaxy, while the

[OIII]/[OII] ratio shows that the ionization parameter of the GRB 060505 burst site is consistent with the short GRB region of the diagram. Figures 1 and 2 indicate that the ISM properties of both the GRB 060505 burst site and the other regions of the galaxy are consistent with the ISM properties of short-duration GRBs associated with compact-object mergers.

4. ISM PROPERTIES

We calculate metallicities using the R_{23} diagnostic originally described in Kewley & Dopita (2002) and later refined and quantified in Kobulnicky & Kewley (2004). The R_{23} diagnostic is double-valued, so we use the [NII]/[OII] criterion of Kewley & Dopita (2002) to distinguish between the upper ($\log([NII]/[OII]) > -1.2$ and lower ($\log([NII]/[OII]) < -1.2$) R_{23} diagnostics. The [NII]/[OII] ratio is available for five of our long GRB host galaxies as well as all five regions of the GRB 060505 host galaxy and the entire BCG sample. In the absence of the [NII] $\lambda6584$ flux (GRB 010921 and GRB 990712), we distinguish between the branches using the [NeIII]/Hα ratio (Nagao et al. 2006). When neither [NII] nor [NeIII] is available (GRB 051121 and GRB 050416), we calculate the metallicities for both R_{23} branches. For comparison, we also calculate the metallicities using the Pettini & Pagel (2004) [NII]/Hα-metallicity relation for our five long GRB hosts with [NII]$\lambda6583$ line fluxes.

We determine the ionization parameter using the Kewley & Dopita (2002) [OIII]/[OII]-q relation. For the five regions of GRB 060505's host galaxy, we also calculate the age of the young (< 10 Myr) stellar population using the calibration of Hβ equivalent width with age by Schaerer & Vacca (1998). We calculate the Hα luminosities and corresponding star formation rates (SFRs) using the relation of Kennicutt (1998) for the GRB 060505 host regions and our long GRB hosts (Hα fluxes were unavailable for the short GRB hosts). The metallicities, ionization parameters, Hα luminosities, and SFRs are given in Table 1.

We find that the GRB 060505 site has a similar metallicity to the other regions of its host galaxy; the R_{23} diagnostic assigns the GRB 060505 burst site an intermediate metallicity of $\log(O/H) + 12 = 8.57 \pm 0.01$ as compared to the rest of the host galaxy, with an average $\log(O/H) + 12 = 8.62 \pm 0.2$. The Pettini & Pagel (2004), or PP04, relation gives the GRB 060505 site a lower metallicity of $\log(O/H) + 12 = 8.28 \pm 0.01$ than the average metallicity of the other regions ($\log(O/H) + 12 = 8.45 \pm 0.06$), but the difference is within the 0.15

dex errors of the PP04 method. The relative metallicity of the GRB 060505 site to the other regions of the galaxy is dependent on the diagnostic that is used; when the errors of these diagnostics are considered (0.1-0.15 dex), we find no statistically significant difference in metallicity between these five regions.

The ionization parameter of the GRB 060505 site, $\log(q) = 7.49$ cm/s, is unusually low as compared with average ionization parameter of the long GRB host galaxies ($\log(q) = 7.95 \pm 0.28$ cm/s. The ionization parameter of the GRB 060505 site is consistent with the short GRB hosts, which have an average ionization parameter of $\log(q) = 7.36 \pm 0.15$ cm/s.

The ages of the young stellar populations are representative of core-collapse progenitor ages (see Bloom et al. 2002, Berger et al. 2007). While the GRB site's is the youngest at 5.3 ± 0.3, this age is comparable to the 6.1 ± 0.6 age of the young stellar population of the upper bulge, to within the errors.

Finally, the GRB site does not have a high SFR with respect to the other regions of the host galaxy. The SFR of the GRB site is also found to be notably lower than the SFRs of the long GRB host galaxies.

5. CONCLUSIONS

We compare the optical diagnostic emission-line ratios of GRB 060505 with the hosts of unambiguous long- and short- duration GRBs. We show that the emission-line ratios, metallicities, ionization parameters and star formation rates of the GRB 060505 environment are more consistent with the two short-duration GRB hosts that have measured optical emission-line ratios rhan with long-duration GRBs.

We compare the metallicity and SFR of the GRB 060505 star-forming region with four other star-forming regions in the GRB 060505 host galaxy. We find no significant difference in either metallicity or SFR between the GRB 060505 region or the other star-forming regions, including the host galaxy bulge.

We do not find compelling evidence to suggest that GRB 060505 originated in a long-duration core-collapse progenitor. Our emission line diagnostic analysis suggests that the environment of GRB 060505 is more consistent with the host environments of compact-object-merger GRB progenitors. A larger comparison sample of short and long GRBs with emission line spectra may shed further light on the nature of GRB 060505 and other intermediate-duration gamma-ray bursts.

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TABLE 1
ISM Properties of GRB Host Galaxies

Galaxy	z[a]	log(O/H) + 12[b] R_{23}	log(O/H) + 12[b] PP04	log(q)	E($B-V$)	$W_{H\beta}$	Age (Myr)[c]	L(Hα) (ergs s^{-1})	SFR (M$_\odot$/yr)	Refs.[d]
GRB 060505 HOST										
GRB region	0.0889	8.57±0.01	8.28±0.01	7.49	0.13	39.20	5.1±0.2	2.61×10^{39}	0.021	1
Upper bulge	0.0889	8.84±0.01	8.47±0.01	7.66	<0.03	27.22	5.4±0.6	2.38×10^{39}	0.019	1
Middle bulge	0.0889	8.43±0.00	8.50±0.00	7.09	0.59	8.06	7.8±0.4	1.69×10^{40}	0.134	1
Lower bulge	0.0889	8.59±0.01	8.42±0.00	7.25	0.30	12.60	6.7±0.3	5.09×10^{39}	0.040	1
Lower spiral	0.0889	8.60±0.06	8.41±0.04	7.44	<0.03	8.92	7.5±0.4	3.12×10^{38}	0.002	1
LONG GRBs										
GRB 060218	0.0335	8.35±0.01	8.19±0.02	7.78	0.17	⋯	⋯	1.22×10^{40}	0.096	2,3
GRB 031203	0.1055	8.26±0.01	8.17±0.01	8.32	0.03	90.72	4.7 ± 0.1	1.51×10^{42}	11.93	4
GRB 030329	0.1680	8.72±0.03	8.32±0.05	8.08	<0.03	⋯	⋯	2.54×10^{40}	0.201	5,6
GRB 020903	0.2510	8.15[e]	8.00	7.88	0.25	36.08	5.5 ± 0.2	2.57×10^{41}	2.030	7
GRB 010921	0.4510	8.55±0.03	⋯	7.67	0.52	⋯	⋯	8.21×10^{41}	6.486	8
GRB 990712	0.4340	8.43±0.01	⋯	7.74	0.17	⋯	⋯	4.63×10^{41}	3.658	9,10
GRB 980425	0.0085	8.36[e]	8.19	7.86	0.60	⋯	⋯	1.20×10^{40}	0.095	11
SHORT GRBS										
GRB 051221	0.5464	8.25 or 8.80	⋯	7.17 or 7.36	0.34[f]	⋯	⋯	⋯	⋯	12
GRB 050416	0.6528	8.30 or 8.68	⋯	7.38 or 7.53	0.34[f]	⋯	⋯	⋯	⋯	13

[a] Redshifts come from the GHostS database. [b] Errors are propagated from statistical flux errors. These do not include the systematic error introduced by the metallicity calibrations, which are 0.1 dex for the R_{23} metallicities (Kewley & Dopita 2002) and 0.15 dex for the PP04 metallicities (Pettini & Pagel 2004). [c] Ages comes from equations derived for the Schaerer & Vacca (1998) models relating Hβ equivalent widths ($W_{H\beta}$) and the age of the young stellar population. [d] Reference: (1) Thöne et al. (2007), (2) Pian et al. (2006), (3) Wiersema et al. (2007), (4) Prochaska et al. (2004), (5) Gorosabel et al. (2005), (6) Hjorth et al. (2003), (7) Soderberg et al. (2004), (8) Price et al. (2002), (9) Küpcü Yoldas et al. (2006), (10) Christensen et al. (2004), (11) Hammer et al. (2006), (12) Soderberg et al. (2006), (13) Soderberg et al. (2007) [e] Statistical flux errors not available in literature. [f] Derived from the M_B-E($B-V$) relation of Jansen et al. (2001).
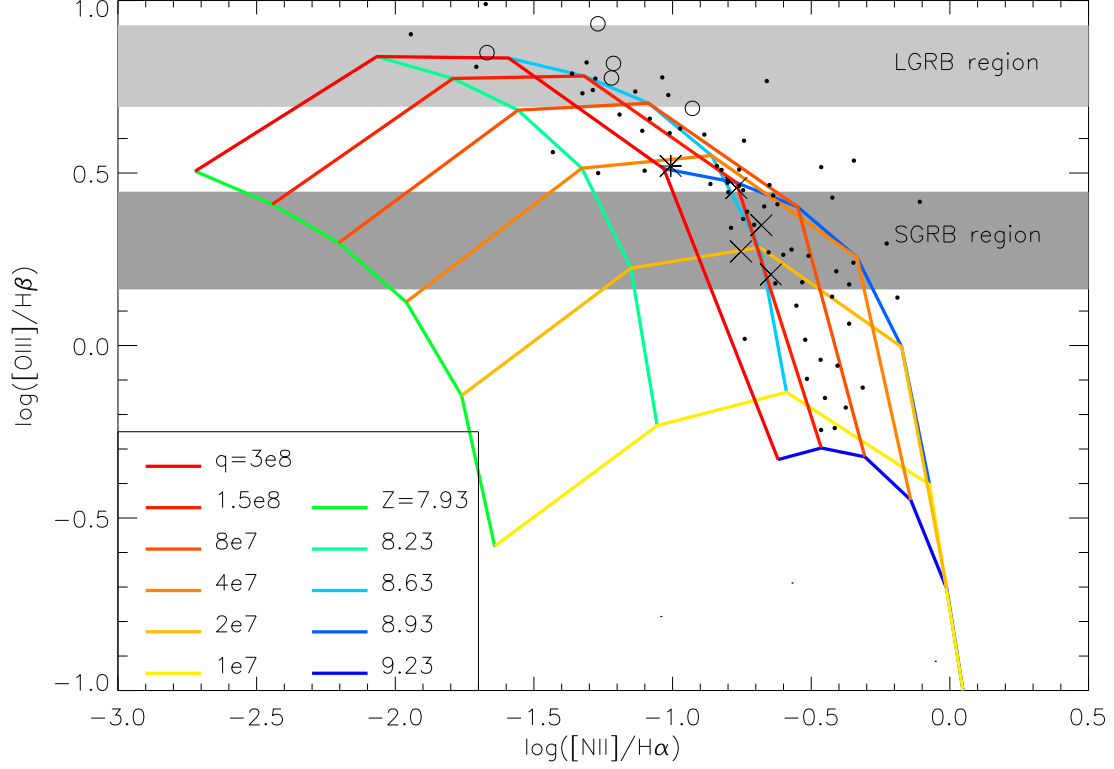
FIG. 1.— Comparison of the [NII]/Hα vs. [OIII]/Hβ diagnostic for the Kong & Cheng (2002) sample of BCGs (small points), the long GRB host galaxies (open circles), the GRB region of GRB 060505's host (star), and several bulge and spiral arm regions of GRB 060505's host (X's). The range of ionization parameters delineated by the location of the long and short GRB hosts are shaded and labeled as shown. The galaxy positions are compared to the photoionization grids of Kewley et al. (2001).
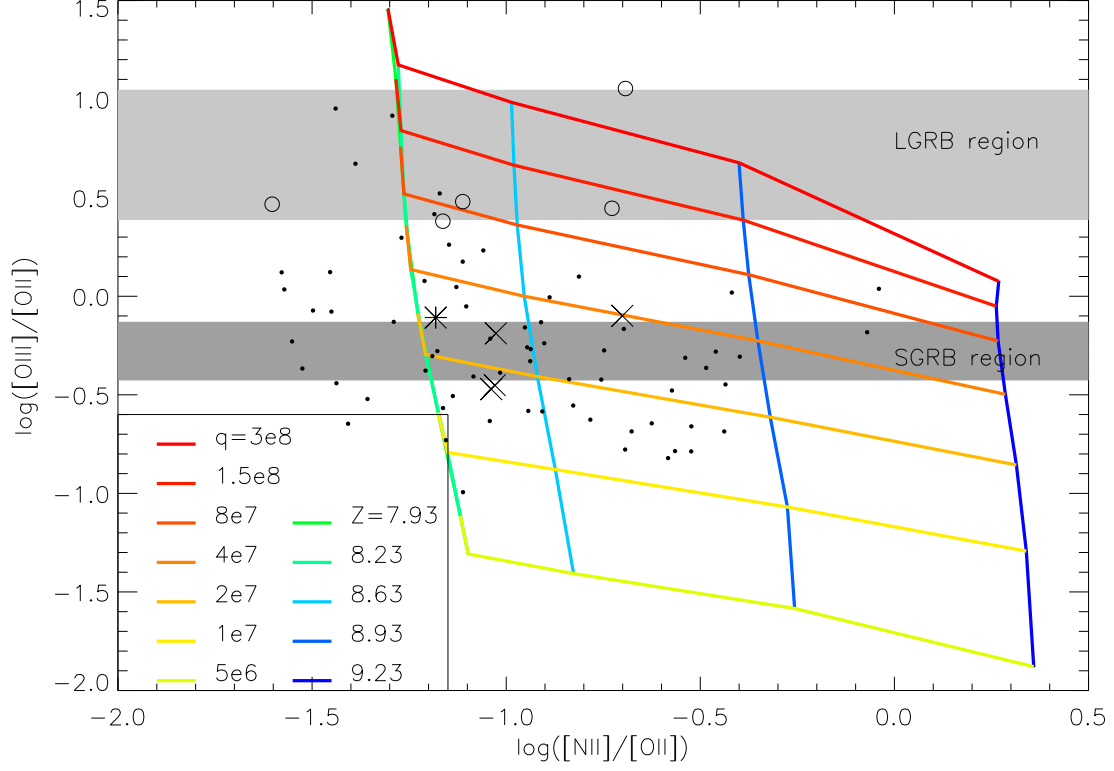
Fɪɢ. 2.— Comparison of the [NII]/[OII] vs. [OIII]/[OII] diagnostic for the Kong & Cheng (2002) sample of BCGs (points), the long-duration GRB host galaxies (open circles), the GRB region of GRB 060505's host (star), and several bulge and spiral arm regions of GRB 060505's host (X's). The range of ionization parameters delineated by the location of the long and short GRB hosts are shaded and labeled as shown. The galaxy positions are compared to the photoionization grids of Kewley et al. (2001).